KERNFORSCHUNGSANLAGE JÜLICH GmbH
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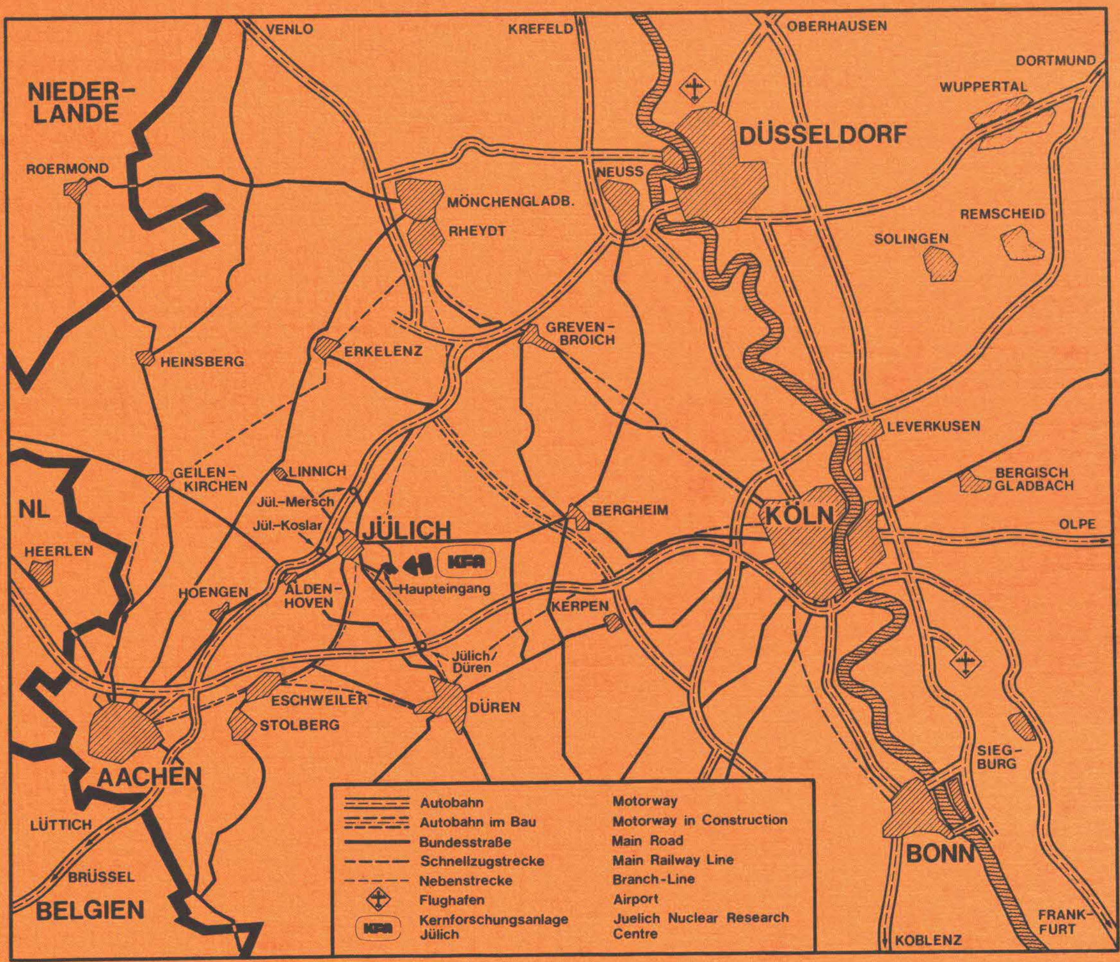
Jül - Spez - 10
Mai 1978
ISSN 0343-7639



Als Manuskript gedruckt

Spezielle Berichte der Kernforschungsanlage Jülich – Nr. 10

Institut für Kernphysik Jül - Spez - 10

Zu beziehen durch: ZENTRALBIBLIOTHEK der Kernforschungsanlage Jülich GmbH,
Jülich, Bundesrepublik Deutschland

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Abstract:

The diffraction angles of the two 24 m curved crystal gamma ray spectrometers at the Grenoble High Flux Reactor are measured with laser interferometers to a precision of about 0.015". The angular steps (0.16") are counted through the interference of linearly and circularly polarized beams.

+ Work performed at Institute Max von Laue - Paul Langevin, Grenoble France

1. Introduction

The measurement of X- or gamma ray energies with diffraction crystal spectrometers requires very accurate determination of the angular orientation of the crystal. In the past the crystal angles were generally set with high precision screws[1]. The angular precision can easily be improved with interferometric measuring devices. These are in principle Michelson interferometers where the lengths of the optical paths are changed by the rotation of mirrors or prisms.

The curved crystal spectrometers Gams 1-2-3 [2,3], which are used for neutron capture gamma ray measurements at the Grenoble High Flux Reactor, have been equipped with laser interferometers. The beam geometry of the Gams 1 interferometer has been adapted from the instrument of G. Borchert[4].

With the 24 m spectrometers Gams 2-3 gamma-ray lines of the widths of only 1" are measured, requiring a step width less than 0.2". Therefore a new interferometer with an interference period of 0.16" was designed. This instrument has a symmetric and compact beam geometry, which permits the use of optical components of small size and relatively low costs. The angular range has been restricted to 4.5°, in keeping with the energy range of the spectrometers.

The degree of angular precision, which is needed for the interferometers, is limited by the accuracy of the determination of line centers in the spectrum. The line shapes observed with the Gams spectrometers may change slightly in a non systematic way, due to some mechanical instability of the (n,γ)-source, which is located in the center of a beam hole. So a precision of 0.02" has been aimed at, corresponding to 1/50 of the line width. The instruments have not been specially adapted for the measurement of fundamental constants and γ-ray standards, which are determined by other authors with extraordinary precisions[5].

2. Principle of the interferometer

Figure 1 shows the optical paths. Deflections of 180° are achieved by means of the totally reflecting isosceles 90°-prisms, which are attached to the unit supporting the diffraction crystal. Rotation of the unit around an axis between the prisms causes changes of the lengths of the light paths of both interferometer branches in opposite directions. Consequently the light intensity at the exit of the interferometer changes periodically permitting the determination of the angle of rotation by an electronic counting system.

In the zero-position the optical paths of the two interferometer branches are equally long. Identical light-intensities, a condition for deep interference minima, are guaranteed by the high degree of symmetry of the two branches. The number of reflections is made equal by means of the mirror M. Furthermore, through the reflection at this mirror, a rather compact construction of the interferometer is made possible.

3. Counting of angular steps

Accidental changes of the angular position of the rotation unit may be caused by even small mechanical shocks, resulting in the passage of interference maxima. Consequently, the decision whether angular steps are to be counted positive or negative, must not be determined solely by the polarity of the driving motor. In order to measure the direction of the actual rotation two interferometer signals are produced which are phase-shifted against each other by 90^{o}.

The light beam which enters the interferometer is linearly polarized. The beam of one of the interferometer branches passes a quartz crystal plate (fig. 1). Because of birefringence in quartz two partial beams are produced which are polarized at right angles to each other and have a phase difference of 90^{o} (circular polarization) after two passages through the quartz plate. A Wollaston prism splits the two partial beams at the exit of the interferometer.

From the analogue signals A and B of figure 2 the square wave functions A' and B' are derived, so that the angular steps can be counted according to the sign of rotation. The counter is enabled only if B' = 1. It counts rising and falling signals of A' up and down respectively. The step width is equal to the length of one period. Figure 3 shows the signals A and B as they have been observed with an oscilloscope, while the driving motor is running at constant speed. The ratio of maximum to minimum light intensity is about 20 : 1.

The two phase shifted analogue signals A and B make possible precise positioning of the rotation unit. When the step counter has arrived at the preset value, the angular position is controlled to equality of these signals (S_n in figure 2). In this way a precision of 1/10 of the step width is achieved.

The step counter is set to zero at a certain reference position which is defined to within 0.03" by means of two electro-mechanical sensors. They are arranged symmetrically with respect to the axis of rotation and their readings are added in order to eliminate translational displacements of the rotation unit. The precision of the reference angular position of 1/3 of the step width allows the complete interferometric step counting system to be checked. Under normally good operation conditions the spectrometers Gams 2 - 3 can run many times through their full angular range without step counting error.

4. Optical and mechanical components

The light source of the interferometer is a standard He-Ne laser (6328 Å, 2 mW) of 1 mm beam diameter. The mirrors (12 Ø or 15 Ø mm x 4 mm) are flat to within $\lambda/50$ only in their central region, because the beam moves on the mirrors by less than 1.5 mm in the total angular range of the interferometer. The mirrors are fixed to an Invar base plate. One of the end mirrors can be adjusted in order to make the two interfering beams parallel to each other. Incomplete adjustment gives rise to a fringe system instead of a field of uniform brightness at the light exit of the interferometer. The interferometer is rotated by a dc-motor via a reduction gear (1 : 6000) and a worm gear (1 : 720). Fine adjustment is achieved with a piezoelectric system (fig. 4).

In order to reduce the relative variations of the wave length of light to less than 10^{-6} the atmospheric pressure inside the interferometer chamber is stabilized to 720 $\pm$ 2 Torr. Complete evacuation of the chamber would have made heat exchange too difficult.

Temperature is controlled to $25^{\circ} \pm 0.05^{\circ}$ C. This precision is needed mainly for the diffraction crystal, since the relative variations of the grating constant must be less than 10^{-6}. Homogeneity of temperature within the interferometer chamber is obtained by air convection using a ventilator.

For perfect operation of the interferometer vibrations must be suppressed. Isolation from ground has been achieved by means of rubber elements which support the interferometer set-up. The eigenfrequency of the system is less than 10 Hertz. Vibrations caused by the driving motor of the rotation unit were reduced by a soft shaft coupling and an elastic suspension of the motor.

5. Angular dependence of the interferometer

The difference ΔL of the optical path of the two interferometer branches varies in the following way with the rotation of the interferometer, assuming precise parallelism of the two prisms

$$\Delta L = 4 \; D \sin \varphi \tag{1}$$

The distance of the prisms is denoted by D, and φ is the angle between the normal on a straight line connecting the prisms (e.g. the two 90°-corners) and the beam direction.

For imperfect parallel adjustment of the prisms, equation (1) must be extended by a correction term C:

$$\Delta L = 4(D \sin \varphi + C\,(\varphi)) \tag{2}$$

In this case D represents the distance of the optical centers of the prisms and φ is related to the line connecting these points. The center of the prism denotes (in a two-dimensional view) the point, around which the prism may be rotated by small angles without changing the length of the light path (see also theory of cube-corner prism[6]).

When a prism is rotated around the point P of figure 5 the optical path length for single 180°-deviation is given by

$$L/2H = A/H \cdot (1 - \cos \alpha) + \sqrt{n^2 - \sin^2 \alpha} - n \tag{3}$$

The index of refraction of the prism material is denoted n. For $\alpha = 0$ one obtains $L = 0$. From equation (3) one can deduce that L is constant for small angles of rotation, if the following relation holds:

$$A/H = 1/n \tag{4}$$

Consequently the center of the prism coincides with the 90°-corner for $n = 1$ (mirrors at 90°). With increasing n the point of rotational invariance moves towards the hypotenuse of the prism. With the help of equations (3) and (4) the correction term C is found to be

$$C/H = (\cos\alpha_1 - \cos\alpha_2)/n + \sqrt{n^2-\sin^2\alpha_2} - \sqrt{n^2-\sin^2\alpha_1} \tag{5}$$

The angles between a line perpendicular to the hypotenuse and the corresponding incident light beam are denoted α_1 and α_2.

The interferometric function, as expressed by equation 1 or 2, shows that the interferometer is not sensitive for translation of the rotation unit. This means that a movement of the axis of rotation, caused for example by the use of standard ball bearings, does not affect the measurement of the angle φ between the rotation unit and the system of fixed mirrors.

Another remarkable property of the interferometer is that the number of angular steps is largely independent of the direction of the incoming light beam. A change of this direction only slightly affects the correction term C (equation 5). Consequently the light-source can be placed outside the region of high dimensional stability.

With $D = 20$ cm and $\lambda = 6328$ Å we obtain for the number of angular steps from equation (1)

$$N = 1.26 \cdot 10^6 \sin\varphi \tag{6}$$

The step width is given by

$$\Delta\varphi = 0.163''/\cos\varphi \tag{7}$$

The wave length of the gamma radiation reflected by the diffraction crystal of grating constant d is determined by the Bragg relation (Laue case):

$$\lambda_\gamma = \frac{d}{m} \cdot \sin \phi \qquad (8)$$

The reflection order is denoted m, and $\emptyset$ is the angle between the incoming gamma radiation and the crystal lattice planes. If the angular position of the rotation unit, where $\emptyset = 0$, is the same as for $\varphi = 0$, linearity between gamma ray wave length and step number is obtained:

$$\lambda_\gamma = \text{const} \cdot N/m \qquad (9)$$

If ϕ and φ are not both zero at the same position of the rotation unit, equation (9) must be extended by a quadratic term (first approximation). This term can easily be determined when a certain gamma line is measured in several reflection orders. Rotation of the diffraction crystal with respect to the interferometer makes this term disappear.

The gamma-ray energy can be deduced from equation (9):

$$E_\gamma = m \cdot K/N. \qquad (10)$$

The calibration constant K is determined by the measurement of gamma- or K-ray lines of precisely known energies. Using quartz crystals reflecting on the 110 planes, we obtain K $\approx$ 3286 MeV.

Relation (9) or (10) allow us to determine the nonlinearity of the system through a measurement of gamma lines in many reflection orders. With the diffraction crystal, which we have chosen, strong lines can be measured in the orders 1 to 5. The Bragg angle of order m expressed in angular steps is given by:

$$N_m = m \cdot N_1 \qquad (11)$$

Measurements have shown that this relation holds with a precision of 1/10 of the step-width ($\sim$0.02"). The remaining discrepancy is equal to the reproducibility of a particular angular position.

The author wishes to express his appreciation for the technical staff members of the ILL, who have participated in the realisation of the interferometers, in particular for Mr. Laroumagne, A. Bresson and G. Schmid. He is furthermore very grateful to Professor O.W.B. Schult for his continous interest in the project and to Drs. H. Börner, W. Davidson, P. Göttel, J. Pinston and R. Roussille for their contributions to the adjustments and tests of the instruments.

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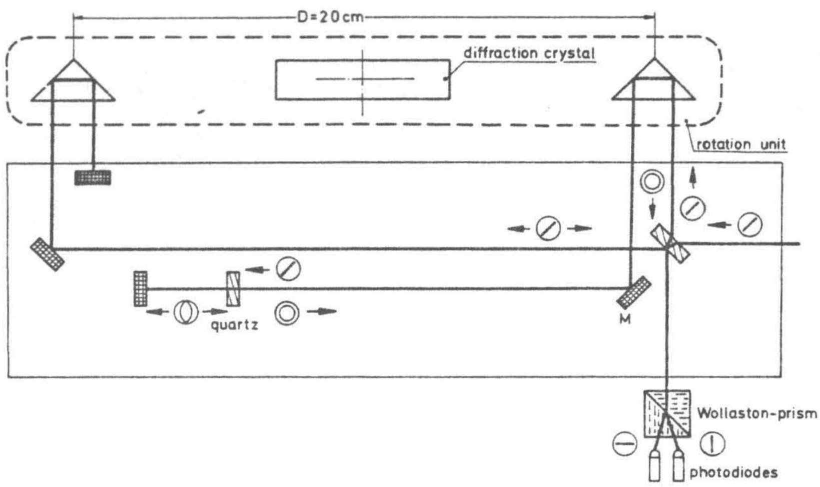

Figure 1: Optical paths in the interferometer

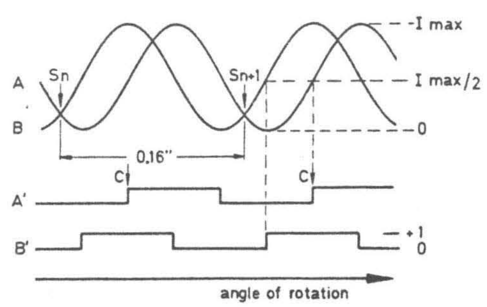

Figure 2: Angular dependence of beam intensities at the output of the interferometer

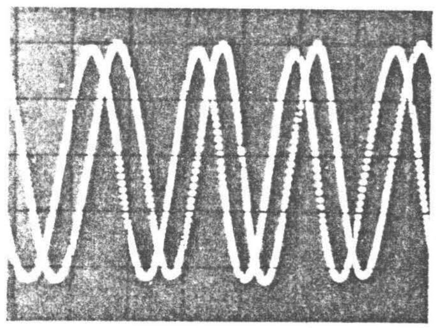

Figure 3: Interferometer signals observed with an oscilloscope

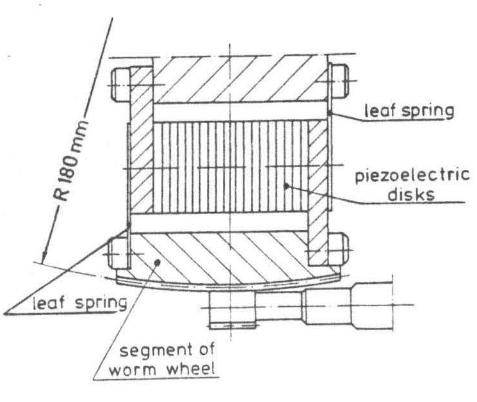

Figure 4: Mechanical system for coarse and fine adjustment of rotation angles

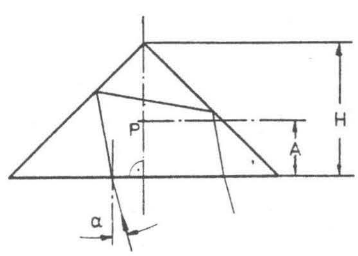

Figure 5: 90^{o}-prism